

A Dedicated MRI Scanner for Radiotherapy Planning: Early Experiences

Gary Liney^{1,2}; Robba Rai¹; Lois Holloway¹; Shalini Vinod¹

¹Liverpool Cancer Therapy Centre, Sydney, Australia

²Ingham Institute for Applied Medical Research, Sydney, Australia

Introduction

The last decade has seen a dramatic increase in the use of MRI for radiotherapy planning. MRI has a number of advantages for the simulation of treatment plans, over the current gold standard of computed tomography (CT); Its excellent and variable soft-tissue contrast has been shown to improve the delineation accuracy

of both the tumor and surrounding organs-at-risk; a range of functional techniques are able to measure and display tumor physiology in the same examination, potentially revealing sub-regions that could receive a boost in radiation dose; and finally, the absence of ionising radiation means the patient may be scanned

any number of times before, during and after treatment, giving the clinician the ability to assess and adapt plans on an individual basis.

MR-simulator

In common with most radiotherapy centres, our department at Liverpool Cancer Therapy Centre (LCTC), located



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The 3 Tesla MAGNETOM Skyra MR-Simulator at Liverpool CTC, in south western Sydney, Australia. The 30 Gauss line can be seen marked on the floor which serves to emphasise this inner controlled area for the majority of our staff who have not previously worked in MRI. The object on the bed is our 3D volumetric distortion test phantom.



2 Photographs showing the RF coil set-up used in head and neck planning scans. **(2A)** Two small flexible coils are placed laterally around the fixation shell using two coil supports. **(2B)** The 18-channel body array is connected to one of the available ports at the bottom of the table using a long cable.

in south western Sydney, relied heavily on local radiology scanners to provide MR images. This often meant a compromise in image protocol and the limited availability of these busy scanners restricted our patient throughput and any opportunity for further development. However, in August 2013, as part of a wider investment in MRI, which will also see the Australian MR-Linac program on site, we installed our own dedicated system for the exclusive use of radiotherapy patients to provide MR-based treatment simulation scans. This scanner is a wide-bore 3 Tesla MAGNETOM Skyra with XQ gradients and 64-channel RF architecture and was purchased with the latest suite of functional imaging sequences. Our MR-Simulator (MR-sim), shown in Figure 1, is configured with a number of radiotherapy-specific features in mind including in-room lasers (as on a CT-simulator), flat indexed table top and a range of RF coils suitable for optimum imaging with the patients in the treatment position. The field strength was chosen with aspirations of incorporating functional studies into future clinical practice.

Over the last 12 months or so, our small but dedicated team has climbed a steep learning curve and implemented MR-based planning successfully into clinical practice for a variety

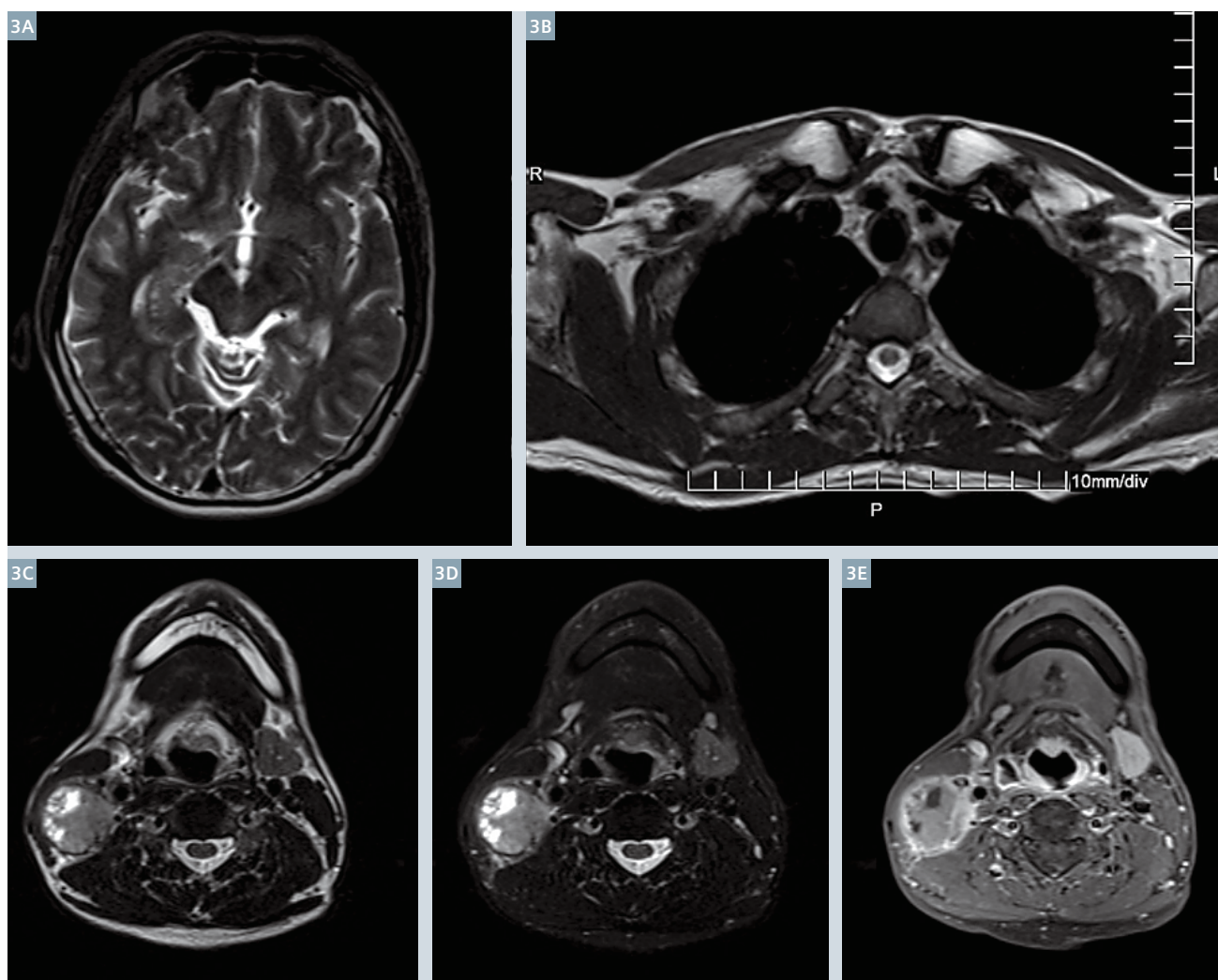
of tumor sites. This process began even before the installation and acceptance testing of the system, with in-house safety and educational training being implemented for all radiotherapy and physics staff connected with MRI. Under normal operation, scanning is performed by our lead MR radiographer and one of a small number of specialist radiotherapists who are rotated through MR-Sim. Additional support is provided by the lead MR physicist and a radiologist. By preserving a significant portion of scan time during the week for research – one of the many advantages of having our own system – we have also been able to develop a number of studies that are beginning to explore the use of functional information and motion evaluation in treatment planning. This article serves as a brief illustration of how we are using this system in practice.

The vast majority of our workload requires MRI to be registered to CT for the electron density information needed in the dose calculation. To facilitate this, we image our patients in the treatment position and take advantage of the RF coils we have available. A good example of this is in head and neck tumors where patients lie on a flat table top and are imaged

in a fixation shell placed over their head and shoulders which is attached to the table. Previous attempts to cater for this equipment on other scanners were compromised either due to a narrower 60 cm bore or unsuitable RF coils. On the MR-Sim we take advantage of the in-built 32-channel RF coil under the flat table-top and use this in conjunction with two laterally positioned 4-channel flexible coils attached to a supporting bridge. More recently we have been able to add an 18-channel body array connected at the foot of the table by a long cable (Fig. 2). This gives us vastly improved signal-to-noise ratio (SNR) and greater coverage compared to what had previously been possible as shown in Figure 3.

Imaging details

In working up our protocols, we have had to consider the specific requirements of MR-simulation, which is often quite different from standard diagnostic procedure [1]. Geometric distortion is something we have to be especially mindful of. For radial distances less than 15 cm from isocentre (i.e. up to 30 cm FOV), system distortions caused by non uniformity in B_0 and non linearity of the gradients are within our tolerance, and the dominant contribution is instead

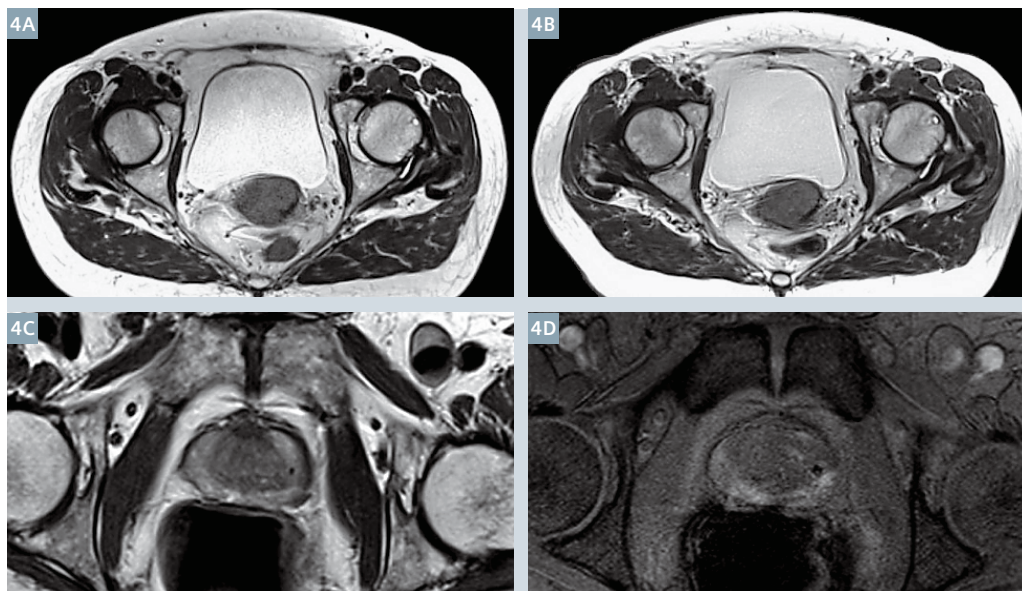


3 Example images acquired in a head and neck tumor patient. Figures **3A** and **B** serve to illustrate the image quality and coverage obtained using dedicated RF coils which extend from midbrain down to sternal notch. The bottom images show a slice taken through the tumor using **(3C)** Dixon T2w in-phase, **(3D)** water-only and **(3E)** Dixon T1w water-only post-contrast.

from chemical shift and magnetic susceptibility within the patient. These effects can be mitigated by use of high receiver bandwidths which we set to 440 Hz/pixel or greater. The large coverage that is required for planning creates long scan times compared to diagnostic practice and we rely heavily on iPAT technology to keep these down to an acceptable level. Nevertheless, these scan times inevitably result in some organ motion and we have found BLADE to be useful in reducing artifacts for example from bladder filling. One of our current studies is comparing the image quality of this radial *k*-space technique against the administration of anti-peristaltic agents and normal cartesian acquisition as

shown in Figure 4A. Another particular interest for us is the development of a single planning scan for prostate patients with fiducial gold seeds. These exams would normally require two separate scans, a gradient-echo based sequence to identify the seed position and a second T2-weighted TSE for contouring the gland. The susceptibility artefact from the seed, while making them clearly visible, reduces positional accuracy, even with high bandwidths, and the requirement for two scans is less than ideal. However, we have begun looking at sequences such as turbo gradient spin-echo (TGSE) which offer the potential of combining both types of contrast into a single image (Fig. 4B).

To fully map out the geometric integrity of our system over large volumes, we have designed and built our own 3D phantom which covers 50 cm in each orientation (pictured in the magnet in Fig. 1). This test object has proved particularly useful in demonstrating the role of TimCT in cases when we have needed to exceed our 30 cm rule. By moving the patient through the bore while acquiring thin isocentric sections the distortion limit along the z-axis may be avoided altogether, thereby extending planning coverage. Figure 5 shows an example of this in a particularly difficult sarcoma case where more than 60 cm coverage was requested by the Oncologist and a total of 50 coil elements were used.



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Developing body protocols for RT simulation; A comparison of BLADE (4A) versus anti-peristaltic agent (4B) as an effective control of organ motion artefacts. Use of the TGSE (4C) to provide a prostate planning scan that combines T2w contrast and gold seed visualization. (4D) Standard gradient-echo image used for seed localisation, which exaggerates the dimension of the marker.

Therapy response

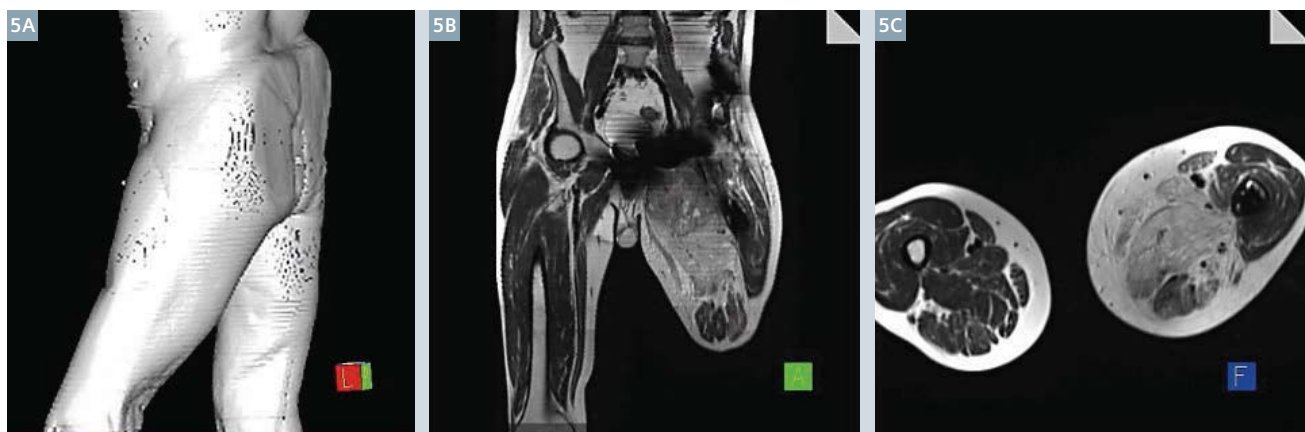
For most examinations we are using MRI at the commencement of treatment for its soft-tissue contrast and the improvement in planning contours. Alongside this routine work, we have begun several research studies that are using MRI to assess response over the course of treatment. These studies use both diffusion-weighted imaging (DWI) and dynamic contrast enhancement (DCE) to look at changes in tumor cellularity and vascularity respectively. In the case of diffusion, the commonly-used EPI sequence produces significant distortions and artifacts that has made its application in radiotherapy plan-

ning problematic. We have recently concluded a study that compared EPI with RESOLVE, which uses multi-segmentation in the frequency encoding direction combined with navigator self-correction, and showed improvements in ADC repeatability and geometric integrity compared to a T2-weighted gold standard [2]. Figure 6 shows a DWI example in a prostate patient acquired with $b = 800 \text{ s/mm}^2$ together with the corresponding ADC map and we have now also adopted this sequence for rectum and cervix. As part of our DCE protocol we acquire pre-contrast

sequences at 2 and 15 degree flip angles to measure the native T1 prior to using dynamically acquired TWIST images. These scans are then analysed using the two compartment model which is available with the Tissue4D software.

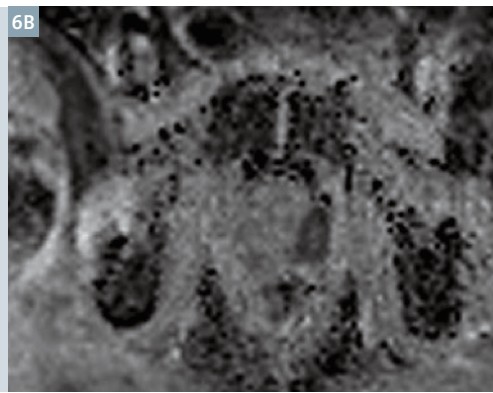
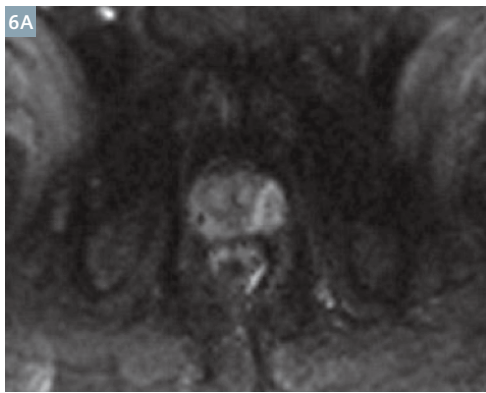
Lung imaging

For our lung patients, we have developed an advanced imaging protocol providing a comprehensive assessment of anatomy, function and motion throughout their treatment (Fig. 7). For tumor contouring a T2-weighted HASTE sequence with a phase



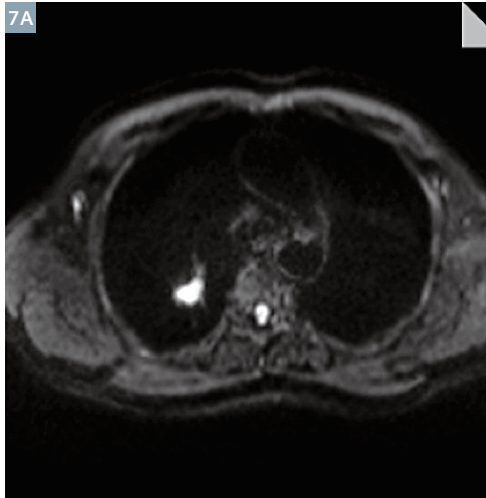
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TimCT was used in this patient with a leg sarcoma and prosthesis *in situ* who could not straighten the effected leg. A full treatment simulation coverage of 61 cm in the head to foot direction was obtained by using the continuously moving table technique.



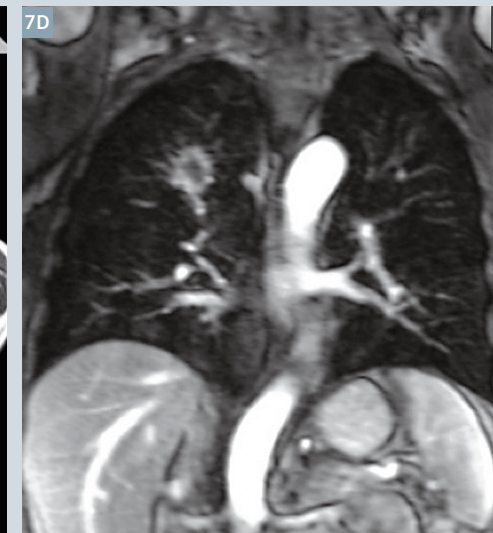
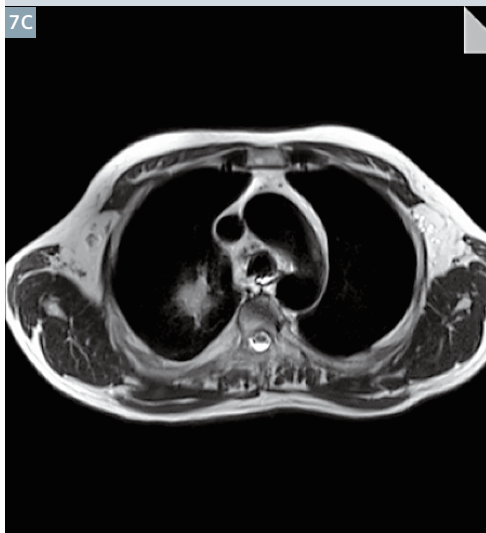
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Diffusion-weighted imaging using the RESOLVE sequence in the prostate; **(6A)** A distortion free image with $b = 800 \text{ s/mm}^2$ and **(6B)**, the resulting ADC map, both of which demonstrate an area of reduced diffusion in the left peripheral zone.



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Example images from a lung tumor patient study; **(7A)** DWI with $b = 500 \text{ s/mm}^2$ image, **(7B)** single frame from a coronal TrueFISP cine sequence acquired with cardiac shim, **(7C)** a late post-contrast enhanced TWIST image and **(7D)** axial HASTE acquired using a phase navigator.

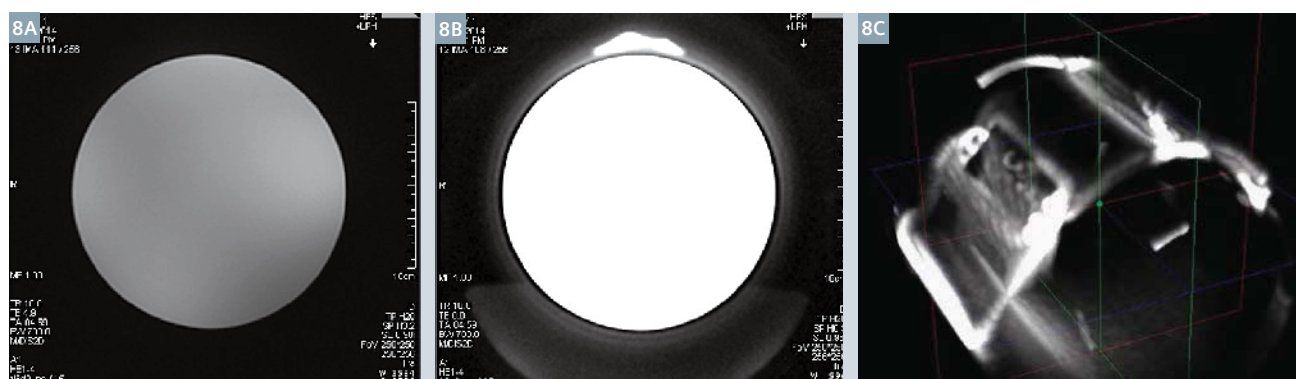


navigator placed in the liver dome is used to provide artefact free images. We then acquire a diffusion-weighted sequence to measure ADC, and cine TrueFISP scans during free breathing to assess tumor motion. The protocol is completed with a DCE TWIST sequence which is modified to acquire

a total of six separate short breath-hold windows from early first pass to 5 minutes post contrast. The incorporation of all this data is still in its infancy but we have already begun to use our own analysis to look at the tumor excursion and how it correlates with respiration.

Conclusion

In the future, we anticipate that it will be possible to replace CT altogether in the majority of cases. In order to do this, one of the challenges will be the need to substitute CT and provide a surrogate for electron density. As part



8 Examples of UTE imaging; **(8A, B)** Test object imaged at 4 ms displays signal from the fluid only but when this is repeated at 0.04 ms (40 μ s) a previously invisible lump of adhesive putty placed on top and the plastic cushion underneath can also be seen. **(8C)** 3D rendering of a processed dataset which demonstrates the RF coil itself (courtesy Jason Dowling, CSIRO).

of our research agreement with Siemens we are currently investigating the efficacy of ultrashort echo time (UTE) sequences to develop a strategy for MR-only planning*. By bringing the TE down to tens of microseconds it becomes possible to obtain signal from materials and tissues that were previously invisible (Fig. 8). These images have the potential to provide more accurate substitute CT datasets as they can map cortical bone and even the RF coil itself which will be useful on the MR-Linac.

In summary, although it is still very much early days for us, the installation of a dedicated scanner in our department has been a great success and crucial in propelling MRI into our practice. We hope that in the not-too-distant future, MR-Sim will become a fairly standard sight in many radiotherapy centres throughout Australia and indeed the rest of the world. This will certainly help to establish a standardised approach for the implementation of MRI into radiotherapy so that the full benefit of this modality can be realised.

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References

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*WIP, the product is currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured.



Contact

Conjoint Associate Professor Gary Liney (UNSW)
Hon Principal Fellow, University of Wollongong
Ingham Institute for Applied Medical
Research & Radiation Oncology
Liverpool Hospital, 1 Campbell Street
Liverpool NSW 2170, Australia
Phone: +61 2 8738 9221
gary.liney@sswahs.nsw.gov.au